NASA RESEARCH GRANT
FINAL REPORT

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Title:	Microphysics and Radiative Properties of Cirrus: Instrumentation and Analysis
Type of Report:	Final Report
Principal Investigator:	Dr. John Hallett
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Recipient:	Desert Research Institute 2215 Raggio Parkway Reno NV 89512-1095
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SUMMARYOF RESEARCH

Work under this grant has involved further development of a new aircraft instrument (the cloudscope) for real time characterization of atmospheric particulates together with field observations of such particulates, both in the form of ice and also as nuclei responsible for nucleation of both ice and water cloud particles. Part of the work involving assessment of the frequency of ice crystal shapes has been carried out in collaboration with the Meteorological Service of Canada; part of the work in a field program with the NCAR C-130. Part of the work has been interpreted in terms of laboratory simulation of ice crystal growth under a wide variety of conditions carried out under a grant from Physical Meteorology Program, National Science Foundation.

FINDINGS

a. Instrumentation and Analysis.

The Cloudscope, an instrument which captures and processes nuclei, ice particles and drizzle drops was further developed for aircraft operations in the Arctic to provide, as two separate instruments, a capability of a field of view 1/2 mm or 1 cm. The former was used for a study of ultra giant hygroscopic nuclei (**b.** below); the latter for larger ice particles to determine their density and density gradient from a measurement of their evaporation rate on heating (**c.** below). Software was further developed to provide the evaporation rate of such particles having different shape to speed the analysis. (Hallett et. al 1998, Meyers and Hallett 2001)

b. Ultra Giant Hygroscopic Nuclei.

The cloudscope was deployed in FIRE-ACE from Fairbanks April/May 1998 on the NCAR C-130 during flights over the Beaufort Sea to measure hygroscopic nuclei for dry diameter > 1μm. Particles were collected on a forward facing optical flat and video imaged from behind; the collecting window could be heated to induce crystallization of solution particles. Alternatively the particles could be observed to grow on entry into moister conditions implying that they were hygroscopic. Particles were found in concentrations up to 4 per liter and diameter up to 11 μm dry size. On occasion, no particles at all were found, implying a concentration of less than one in 60 liters. Comparison with CCN measurements showed concentrations between 200 and 400 cm^{-3} (active between 0.04 and 1% supersaturation) with no obvious relationship to UGN concentration. It was concluded that a significant gap in measurement capability existed between 0.1 and μm; it was further concluded that the concentration of UGN particles was highly variable both with altitude and location and between different days. It is argued that since particles in this size range may be responsible for nucleation of both drizzle drops and ice particles cloud may be readily removed as ice or drizzle or persist depending on the presence or absence of this size of hygroscopic particle. There are thus major implications for the persistence or otherwise of cloud depending on the presence or otherwise of such nuclei and the radiative impact of such clouds. It may further be hypothesized that such nuclei are responsible for most supercooled drizzle and hence associated aircraft icing hazards. (Meyers and Hallett 2001; Hallett and Isaac 2002)

c. Ice Particle Density.

Measurements have been made of ice particles collected in Florida and in the Pacific to determine the range of densities from the viewpoint of finding the vertical mass flux of precipitation from measured images. The basic measurement is the area of the collected particle and its rate of change as the particle evaporates. The area relation rate gives the particle density directly; a constant density particle gives linear area - time evaporation. Ice particle density is found to range over 0.05 - 0.9 g cm^{-3}. Should the particle density vary with location, the relation is no longer linear and a changing density can be determined. Integration gives the particle mass and mean density; a knowledge of environmental conditions and an estimate of drag coefficient gives the fall velocity and hence, integrated over particle size of a sample, a vertical mass flux. (Kingsmill et. al 2000; Hallett and Isaac 2002)

d. Ice Particle Shape.

The habit of growing ice crystals depends on both temperature and supersaturation of the growth environment. Recent laboratory studies (Bailey and Hallett 2002) have extended earlier work at temperatures from 0 to -20C to below -70C. The temperature - supersaturation map displays a complexity both in habit of individual elements and also in degree of polycrystals. The results suggest that providing the growth temperature is known, the supersaturation (as influenced by fall velocity) can be inferred from growth form. Measurement of ice particle growth shape in the Arctic undertaken with the MRC Convair aircraft under a wide variety of conditions using the PMS 2DC and the CVI have demonstrated that most crystals observed (95%) differ dramatically from the idealized pristine forms (plates, columns, dendrites) reported in many studies and often used as a basis for calculation of radiative properties. Interpretation of many of these forms can now be undertaken with reference to the laboratory study.

Further laboratory studies under controlled changes of environmental conditions have demonstrated how drops freeze followed by sequential growth from the vapor and sequential evaporation. These considerations enable different forms of crystals observed to be interpreted in terms of growth and evaporation on frozen drops. Most important is that images showing apparent crystal aggregation can be reproduced in the laboratory in terms of growth from the vapor alone where such a process could *not* have taken place.

These considerations point to the following conclusions:

- The habit distributions of ice crystals in a given air parcel differed depending on circumstances. Two cases can be identified. First a parcel is cooled by expansion and crystal, forms follow the temperature/ supersaturation history of the parcel. The habits follow the detail of the ice nucleation process and sometimes multiple habits occur. An alternative scenario is that ice forms in a similar way but in multiple layers in the vertical such that ice from above falls to a cloud below. Thus a bimodal or multimodal spectrum may occur. These considerations have major implications for how spectra are to be specified under different formation conditions and the associated algorithms.

- The radiative properties of most ice crystal clouds are determined by properties of irregular shaped crystals rather than pristine crystals.

- The temperature near -41 C is critical for two reasons: homogeneous nucleation of supercooled droplets takes place; bullet rosettes form from such nucleation and grow at a faster rate than the more compact polycrystals which nucleate and grow elsewhere. (Korolev et. al 1999; Korolev et. al 2001; Korolev et. al 2002, Korolev et. al 2003; Hallett et. al 2001; Bailey and Hallett 2002a; Bailey and Hallett 2002b; Bailey et. al 2002)

e. Contrail Ice.

The laboratory results apply equally to contrail produced ice with the proviso that the nucleation takes place rapidly as the exhaust cools and ice growth is then specified by the ambient temperature and a supersaturation predicated by a concentration determined by the initial turbulence and the final ice concentration and size. In this case at a known temperature and measured concentration and size, a supersaturation for the growth of the particles should be possible. The observed trigonal symmetry is a bit of as a mystery here. (Hallett et. al 1999; Hallett et. al 2001)

f. Conclusions.

It is concluded that any future aircraft study of ice at low temperature must take into account the considerations discussed above particularly in the way the measurements are made and the flight protocols for the aircraft. In the absence of such an approach the results will be almost impossible to interpret in terms of any realistic physical regime.

Publications funded or partly funded under this grant:

Arnott, W.P., C. Schmitt, Liu, Y. and J. Hallett, 1998: Droplet size spectra and water-vapor concentration of laboratory water clouds: inversion of Fourier transform infrared (500-5000 cm^{-1}) optical-depth measurement. *Appl. Optics,* **36,** 5205-5216.

Bailey, M. and J. Hallett, 2002: Nucleation, Growth and Habit Distribution of Cirrus Type Crystals Under Controlled Laboratory Conditions. *Q.J.R. Meteorol. Soc.*, **128,** 1461-1484.

Hallett, J. W. P. Arnott, R. Purcell and C. Schmidt, 1998: A Technique for characterizing Aerosol and Cloud Particles by Real Time Processing. *$PM_{2.5}$: A fine particle standard Proceedings of an International Specialty Conference,* Sponsored by *EPA Air and Waste Management Association,* Ed. By J. Chow and P. Koutrakis, 1998, **1,** 318-325.

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Korolev, A., G.A. Isaac, and J. Hallett, 2000: Ice particle habits in stratiform clouds. *Q.J.R. Meteorol. Soc.,* **126,** 2873-2902.

Korolev, A.V., G.A. Isaac and J. Hallett, 1999: Ice particle habits in Arctic clouds. *Geophys. Res. Ltrs.,* **26,** 1299-1302.

Korolev, A.V., G.A. Isaac, S.G. Cober, J.W. Strapp, and J. Hallett, 2002: Microphysical Characterization of Mixed Phase Clouds. *Q.J.R. Meteorol. Soc.*, in press.

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Poellot, M. R., W. P. Arnott, and J. Hallett, 1999: In situ observations of contrail microphysics and implications for their radiative impact. *J. Geophys. Res.,* **104,** 12077-12084.

Other Publications related to this grant:

Foster, T.C. and J. Hallett, 2002: The Alignment of Ice Crystals in Changing Electric Fields. *Atmos. Res.*, **62**, 149-169.

In preparation:

Bailey, M. J. Hallett, A. Korolev and G. Issac, 2002: Laboratory simulation of ice crystal habit related to climate aircraft observation.

Conference presentations:

Bailey, M. and J. Hallett, 2002: Growth Characteristics of Laboratory Grown Ice Crystals Between –20C and –70C. *AMS 11th Conference on Cloud Physics*, 3-7 June 2002, Ogden, UT. (CD) 3.3

Bailey, M., J. Hallett, a. Korolev, and G. Isaac, 2002: Laboratory Growth, Sublimation and Regrowth of Ice Crystals. *AMS 11th Conference on Cloud Physics*, 3-7 June 2002, Ogden, UT. (CD) P1.4

Bailey, M. and J. Hallett, 2000: Nucleation, growth and habit distributions of cirrus type crystals under controlled laboratory conditions. *13th International Conference on Clouds and Precipitation*, 14-18 August, Reno, Nevada. Desert Research Institute, Reno, Nevada; Editors: J. Hallett and G.A. Isaac, Proceedings, **1**, 629-632.

Hallett, J. and G.A. Isaac, 2002: Aircraft icing in glaciated and mixed phase clouds. *40th AIAA Aerospace Sciences Meeting and Exhibit.* 14-17 January 2002, Reno, NV. AIAA 2002-0677.

Hallett, J., M. B. Meyers, M. P. Bailey, W. P. Arnott, B. Strauss and P. Wendling, 1999: The Morphology of Ice Crystals in Aircraft Contrails. *37th AIAA Conference on Aerospace Sciences Meeting and Exhibit,* 11-14 January, 1999, Reno, Nevada, 1-11.

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Korolev, A., G.A. Isaac, and J. Hallett, 2000: Ice particle habits in stratiform clouds. *13th International Conference on Clouds and Precipitation*, 14-18 August, Reno, Nevada. Desert Research Institute, Reno, Nevada; Editors: J. Hallett and G.A. Isaac, Proceedings, **2**, 709-712.

Meyers, M. B., J. Hallett, W. P. Arnott and J. Niehues-Brooks, 1999: Aircraft Observations of Giant Nuclei in Arctic Regions. *AMS 5th Conference, Polar Meteorology and Oceanography,* Dallas, Texas, 188-191.

Students supported or partly supported by this grant:

Kenneth Depauli, undergraduate student (hourly) in geology, University of Nevada, Reno, working on analysis of cloudscope data.

Matthew Meyers, M.S., 1999, Atmospheric Sciences, University of Nevada, Reno. Dissertation Title: An Assessment of Aircraft Mounted Cloud Probes and their Measurement Characteristics in a Highly Variable Atmosphere.

Brett Garner, M.S., 2001, University of Nevada, Reno. Dissertation title: On the Density of Atmospheric Particles.

German Viduarre, Ph.D. student in cloud physics, University of Nevada, Reno, working on problems of aircraft icing.

Post Doctoral Appointment:

Dr. Matthew Bailey (partial support): Comparison of cirrus crystals measured by cloudscope and replicator with crystals nucleated and grown under simulated conditions in the laboratory. Dr. Bailey currently has a faculty appointment at Desert Research Insitute.